Optimization of conjunctive water supply and reuse systems with distributed treatment for high-growth water-scarce regions

NSF EFRI – RESIN

$2M grant over 4 years

Emerging Frontiers of Research and Innovation

Resilient and Sustainable Infrastructures
Participants

Kevin Lansey (CE)
Robert Arnold (Environ. Eng.)
Guzin Bayraksan (Systems Eng.)
Christopher Choi (Ag and Bio. Eng.)
Christopher Scott (Udall Public Policy)
Steve Davis (Malcolm Pirnie)
Doosun Kang (CE Post-Doc)

Majed Akhter
Alex Andrade
Ronson Chee
Kerri Jean Ormerod
Pierre Peguy
Pedro Romero
Anne Stewart
Gwen Woods
Weini Zhang
Several undergraduate students and MP staff
Brian Keller (graduated)
Partners

Global Water

Pima County Department of Wastewater Management

Tucson Water
Historic and projected water demand in the Tucson Active Management Area (using data from City of Tucson (2004))
Is water reclamation the next bucket?

NAE grand challenge: “Combined neighborhood” of urban water and wastewater systems

Decentralized/satellite treatment - Where and how to treat?

Dual distribution systems - How to distribute and for what uses?
Utility Goals

- Reliably satisfy water demand and water quality needs
- Triple bottom line objectives
  - Construction and operational costs
  - GHG and impact of releases to environment
  - Institutional/regulatory compliance and social acceptance
- All under an uncertain future
Project Goals

Optimize real and randomly generated systems to analyze the effects of:

- institutional, legal and social constraints and
- topology and spatial land development patterns

on the optimal layout and design of integrated water supply/wastewater treatment services and assess

- the resiliency and sustainability of the system to withstand supply, energy and mechanical disruptions and
- the system objectives in terms of dollars, energy, and GHG production
Model dual supply systems
- Hydraulics
- Economics
- Energy
- GHG production
- Water quality
- Reliability

Model regional supply systems
- Water Demands
- Economics
- Energy
- GHG production
- Supply and Demand uncertainty
- Quantify Resilience/sustainability

Optimize dual supply systems

Bayraksan & Lansey

Optimize regional supply systems

Optimize complete water reclamation/supply system

Arnold & Davis

Public education and utility tools

Utility input & support

Assess social institutional, legal constraints and goals

On the ground applications

Life cycle cost analysis

Scott

Lansey & Choi

All
Economies of Scale vs Pumping Cost

Regional Wastewater Reclamation Facility (WRF)

Regional WW Interceptors

Regional RW Transmission

Satellite WWRF

Local RW Distribution

Use Area
Decision Support System (DSS)

- Malcolm Pirnie, Inc. under WateReuse Foundation project
- Can compares regional and satellite treatment
- Costs
  - wastewater treatment
  - distribution +/- or recharge of reclaimed water
- Other criteria (e.g., reliability, environmental factors) in a weighted decision matrix
- Will be linked with education and optimization tools
HAMP Reclamation Scenarios

**Scenario 1: No Reclamation**
- 16.5 mgd potable water from Hayden Udall WTP
- 12 mgd wastewater to Roger Rd WWRF

**Regional Reclamation**
- 13.5 mgd potable water from Hayden Udall WTP
- 12 mgd wastewater to Roger Rd WWRF
- 3 mgd reclaimed water to HAMP

**Satellite Reclamation and Groundwater Recharge**
- 13.5 mgd potable water from Hayden Udall WTP
- 5 mgd wastewater to Roger Rd WWRF
- 4 mgd to Rillito River for groundwater recharge
- 3 mgd reclaimed water used in HAMP
### HAMP Scenarios: Results

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Potable System Cost</th>
<th>Wastewater/Reclaimed System Cost</th>
<th>Total Cost (20 year present worth)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No reclamation</td>
<td>$840 million</td>
<td>$180 million</td>
<td>$1020 million</td>
</tr>
<tr>
<td>Regional reclamation</td>
<td>$590 million</td>
<td>$230 million</td>
<td>$820 million</td>
</tr>
<tr>
<td>Satellite reclamation</td>
<td>$590 million</td>
<td>$205 million</td>
<td>$795 million</td>
</tr>
</tbody>
</table>

- If groundwater recharge is valued at $1000/acre ft, the recharge option is worth $4.7 million annually.

- Assumptions:
  - New supply line from WTP (versus expansion of existing lines)
  - Neglect expansion of WW collection system
  - Neglect expansion of reclaimed water pipeline
Dual distribution systems

What flow to provide through each system?

**Potable**

**Irrigation**

**Toilet**

**Fire flows**

Parallel Pipe System

**WTP**

**Non-potable water (Reclaimed water)**

**WWTP**

Potable

Irrigation

Toilet

Fire flows
# Optimal cost comparison

(minimize costs: pump/pipes/O&M)

<table>
<thead>
<tr>
<th>Water use</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P*</td>
<td>NP**</td>
<td>P</td>
<td>NP</td>
</tr>
<tr>
<td>Drinking</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Toilet</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Outdoor</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Fire</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Ind. System</td>
<td>2,507,245</td>
<td>1,752,069</td>
<td>1,175,731</td>
<td>1,650,095</td>
</tr>
<tr>
<td>Cost ($)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost</td>
<td>2,507,245</td>
<td>2,927,799</td>
<td>3,088,246</td>
<td>2,901,584</td>
</tr>
</tbody>
</table>

(↑ 16.8%)
(↑ 23.2%)
(↑ 15.7%)
Historical and Projected Demand & Supply

- **Full Allotment**: 262,490 afy
- 80% of total effluent production from all plants

Graph depicting demand and supply from 1985 to 2050, with categories:

- **Total Demand**
- **Natural Recharge**
- **Incidental Recharge**
- **Effluent Water Reuse**
- **CAP Delivery**
Historical and Projected GW budgets

GW budget = \( \sum \text{Supply} - \sum \text{Demand} \)
Sustainability Measures (using GW budgets)

1. Reliability (1 - failure frequency): R1
   \[ \text{No. of satisfactory values / Total no. of simulation periods} \]

2. Resiliency (failure duration): R2
   \[ 1 / \text{Average duration of unsatisfactory events} \]

3. Vulnerability (magnitude of failure): R3
   \[ 1 - \left( \frac{\text{Sum of individual unsatisfactory values}}{\text{Max. among all alternatives}} \right) \]

4. Restorability (magnitude of success): R4
   \[ \frac{\text{Sum of individual satisfactory values}}{\text{Max. among all alternatives}} \]

Sustainability Index (weighted average of R1~R4)
\[ W1*R1 + W2*R2 + W3*R3 + W4*R4, \text{ where } W1+W2+W3+W4=1 \]

Note) All measures range [0, 1]
Zero(0) for least sustainable and One(1) for most sustainable condition
Sustainability Measures
(Illustrative example)

R1 (reliability) = 5 / 10 = 0.5
R2 (resiliency) = 1 / ((2+1+2)/3) = 0.6
R3 (vulnerability) = 1 - (20/25) = 0.2 (*20=5+3+4+6+2, Alter2=25, Alter3=15)
R4 (restorability) = 16/23 = 0.7 (*16=2+6+2+4+2, Alter2=14, Alter3=23)
Sustainability = (R1+R2+R3+R4)/4 = 0.5
Scenario Analysis of the TAMA GW budgets

Base condition

Scenario 1 - 5% increase of demand

Scenario 2 - 5% decrease of demand

Scenario 3 - 10% increase of effluent water reuse

Scenario 4 - Drought every 5 yrs

20% decrease in natural recharge and CAP delivery
### Sustainability Measures

<table>
<thead>
<tr>
<th>Year</th>
<th>GW budget (1000s of AF)</th>
<th>Scenario 1 - 5% increase of demand</th>
<th>Scenario 2 - 5% decrease of demand</th>
<th>Scenario 3 - 10% increase of effluent water reuse</th>
<th>Scenario 4 - Drought every 5 yrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Condition</td>
<td>0.39</td>
<td>0.16</td>
<td>0.53</td>
<td>0.43</td>
<td>0.38</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>0.20</td>
<td>0.15</td>
<td>0.00</td>
<td>0.13</td>
<td>0.12 (↓0.26)</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>0.73</td>
<td>0.45</td>
<td>0.85</td>
<td>1.00</td>
<td>0.76 (↑0.38)</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>0.54</td>
<td>0.32</td>
<td>0.70</td>
<td>0.67</td>
<td>0.55 (↑0.17)</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>0.32</td>
<td>0.21</td>
<td>0.13</td>
<td>0.36</td>
<td>0.26 (↓0.12)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Reliability (R1)</th>
<th>Resiliency (R2)</th>
<th>Vulnerability (R3)</th>
<th>Restorability (R4)</th>
<th>Sustainability</th>
</tr>
</thead>
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<td>Base Condition</td>
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<td>0.16</td>
<td>0.53</td>
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<td>0.38</td>
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<td>Scenario 1</td>
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<td>0.13</td>
<td>0.36</td>
<td>0.26 (↓0.12)</td>
</tr>
</tbody>
</table>
## Design Uncertainties

<table>
<thead>
<tr>
<th>Scale: Temporal → Spatial ↓</th>
<th>Operational (months to several years)</th>
<th>Strategic (10 – 100 years)</th>
</tr>
</thead>
</table>
| **Conventional system** (independent supply, reuse) | • Mechanical performance  
• Supply disruptions | • Capacity exceedance  
• Excess/wasted reclaimed water |
| **Conjunctive system** (with decentralized treatment) | • Conjunctive operations  
• Financing issues  
• Regulatory compliance (water quality, CO₂ emissions caps) | • Technical obsolescence  
• Community growth  
• Water resource variability  
• Public perceptions of reuse and decentralized treatment |
| **Water resources system** | • Proportions from multiple sources (groundwater, imported, reclaimed)  
• Quality blend issues | • Climate change  
• Drought |
# Tucson general survey -- acceptable urban uses

## Outdoor uses

<table>
<thead>
<tr>
<th>Use</th>
<th>Oppose</th>
<th>Unsure</th>
<th>Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire hydrants*</td>
<td>2%</td>
<td>95%</td>
<td></td>
</tr>
<tr>
<td>Cemetery/golf courses*</td>
<td>7%</td>
<td>89%</td>
<td></td>
</tr>
<tr>
<td>Household lawns*</td>
<td>7%</td>
<td>88%</td>
<td></td>
</tr>
<tr>
<td>Public parks/schools*</td>
<td>12%</td>
<td>82%</td>
<td></td>
</tr>
<tr>
<td>Groundwater recharge*</td>
<td>29%</td>
<td>48%</td>
<td></td>
</tr>
</tbody>
</table>

## Indoor uses

<table>
<thead>
<tr>
<th>Use</th>
<th>Oppose</th>
<th>Unsure</th>
<th>Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toilets*</td>
<td>13%</td>
<td>8%</td>
<td>79%</td>
</tr>
<tr>
<td>Swamp coolers</td>
<td>30%</td>
<td>22%</td>
<td>48%</td>
</tr>
<tr>
<td>Laundry</td>
<td>32%</td>
<td>27%</td>
<td>41%</td>
</tr>
<tr>
<td>Cleaning</td>
<td>42%</td>
<td>29%</td>
<td>29%</td>
</tr>
<tr>
<td>Bathing</td>
<td>53%</td>
<td>27%</td>
<td>20%</td>
</tr>
<tr>
<td>Cooking</td>
<td>65%</td>
<td>25%</td>
<td>10%</td>
</tr>
<tr>
<td>Drinking</td>
<td>66%</td>
<td>26%</td>
<td>8%</td>
</tr>
</tbody>
</table>

*Approved uses for reclaimed water per Arizona Administrative Code*
Existing residential reclaimed water users’ acceptance of potential reclaimed water uses

<table>
<thead>
<tr>
<th>Reclaimed Water User Study (General)</th>
<th>% Agree/ strongly agree</th>
<th>% Disagree/ strongly disagree</th>
<th>% Unsure</th>
</tr>
</thead>
<tbody>
<tr>
<td>groundwater replenishment</td>
<td>75/(48)</td>
<td>11/(29)</td>
<td>14/(22)</td>
</tr>
<tr>
<td>swamp coolers</td>
<td>51/(48)</td>
<td>28/(30)</td>
<td>21/(22)</td>
</tr>
<tr>
<td>laundry</td>
<td>35/(41)</td>
<td>45/(32)</td>
<td>21/(27)</td>
</tr>
<tr>
<td>toilet</td>
<td>84/(79)</td>
<td>14/(13)</td>
<td>3/(8)</td>
</tr>
<tr>
<td>swimming</td>
<td>32/*</td>
<td>50/*</td>
<td>22/*</td>
</tr>
<tr>
<td>car washing</td>
<td>78/*</td>
<td>15/*</td>
<td>7/*</td>
</tr>
<tr>
<td>cooking</td>
<td>14/(10)</td>
<td>68/(65)</td>
<td>19/(25)</td>
</tr>
<tr>
<td>drinking</td>
<td>11/(8)</td>
<td>70/(66)</td>
<td>18/(26)</td>
</tr>
</tbody>
</table>

Values in parens are from the Tucson general survey
Who do you trust to provide accurate information about reclaimed water?

<table>
<thead>
<tr>
<th><strong>Who</strong></th>
<th>distrust</th>
<th>neutral</th>
<th>trust</th>
</tr>
</thead>
<tbody>
<tr>
<td><em><strong>researchers</strong></em></td>
<td>8%</td>
<td>18%</td>
<td>74%</td>
</tr>
<tr>
<td><em><strong>water utilities</strong></em></td>
<td>16%</td>
<td>29%</td>
<td>55%</td>
</tr>
<tr>
<td><em><strong>WW treatment facilities</strong></em></td>
<td>17%</td>
<td>37%</td>
<td>46%</td>
</tr>
<tr>
<td><em><strong>federal regulators</strong></em></td>
<td>27%</td>
<td>28%</td>
<td>46%</td>
</tr>
<tr>
<td><em><strong>state regulators</strong></em></td>
<td>25%</td>
<td>30%</td>
<td>45%</td>
</tr>
<tr>
<td><strong>independent consultants</strong>*</td>
<td>23%</td>
<td>45%</td>
<td>32%</td>
</tr>
<tr>
<td><em>local officials</em>**</td>
<td>40%</td>
<td>41%</td>
<td>19%</td>
</tr>
<tr>
<td>national media</td>
<td>41%</td>
<td>42%</td>
<td>17%</td>
</tr>
<tr>
<td>local media</td>
<td>39%</td>
<td>41%</td>
<td>21%</td>
</tr>
<tr>
<td>environmental orgs</td>
<td>21%</td>
<td>29%</td>
<td>50%</td>
</tr>
<tr>
<td>citizen groups</td>
<td>22%</td>
<td>46%</td>
<td>33%</td>
</tr>
<tr>
<td>friends/family</td>
<td>19%</td>
<td>49%</td>
<td>32%</td>
</tr>
</tbody>
</table>

Dependent variable: Would you be willing to drink reclaimed water if it was treated to a water quality level that matched or exceeded your current tap water quality?

* p ≤ .05  ** p ≤ .01  *** p ≤ .001
Aspects of project that will enable potentially transformative results

- Demonstrate Water and Wastewater utility collaborations
- Integration of triple bottom line objectives in particular social/institutional
- Education of water needs and policy impact – facilitated public involvement in water/wastewater decisions
- Combining regional water supply planning with detailed distribution system design
Economic cost breakdown

**Scenario 1**
- pipeCC: 26%
- pipeRC: 20%
- pumpCC: 20%
- pumpOC: 4%

**Scenario 2**
- 47%
- 25%
- 18%
- 10%

**Scenario 3**
- 44%
- 28%
- 19%
- 9%

**Scenario 4**
- 48%
- 25%
- 16%
- 11%
Water Demand/Supply Projections for the Phoenix AMA

Supply/Demand (1000s of AFY)

Year


Natural Recharge
Surface Water
Mined GW
Effluent
Incidental Recharge
CAP Water
Demand
Project Responsibilities

- Monthly full team meetings
- Bi-weekly/weekly sub-group meetings
- Regular partner interactions
- Annual partner summary meetings
- Eight grad students; plans for 2 more with undergraduates

Integrated System Optimization (deterministic & stochastic) (Bayraksan/Lansey)

Integrated Water and Wastewater System Modeling (All)

- Water Quality
  - Arnold, Choi, Davis
- Water Quantity
  - Choi, Lansey
- Energy, GHG
  - Lansey
- Legal and Institutional
  - Scott
- Social/public perception
  - Scott
EFRI-RESIN: Optimization of conjunctive water supply and reuse systems with distributed treatment for high-growth water-scarce regions

Rationale

- Water scarcity – 36 states within 5 years
- Key infrastructures:
  (i) Water supply
  (ii) Wastewater treatment and reuse distribution
- NAE grand challenge: “Combined neighborhood” of urban water and wastewater systems
- Cost, environment, public perceptions matter
- Resilience & sustainability affected by uncertainty
  - Short term – mechanical failures, drought, etc.
  - Long term – growth, climate variability, policies

Approach

- Paradigm shift to resilient, integrated systems
- Optimal design & operation to minimize Triple Bottom Line ($$, environmental, social)
- Decentralized treatment reduces energy & operations costs, increases water reuse
- Non-engineering roadblocks to reuse addressed
- Applications (real + generic) lead to new insights

Impacts

- Interdisciplinary Team
  - Lansey - Civil Engineering & Engr. Mechanics
  - Arnold - Chemical & Environmental Engineering
  - Bayraksan - Systems & Industrial Engineering
  - Choi - Agricultural & Biosystems Engineering
  - Scott - Public Policy; Geography & Reg. Devel.
  - Davis - Malcolm Pirnie Consulting Engineers

Results - Cost Comparisons